

NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

L95744

ESTIMATING THE RELATIONSHIPS BETWEEN THE
STATE OF THE ART OF TECHNOLOGY AND
PRODUCTION COST FOR U.S. AIRCRAFT

by

Robert E. Lowe

June 1989

Thesis Advisor:

O. Douglas Moses

Approved for public release; distribution is unlimited

T244012

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b RESTRICTIVE MARKINGS			
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution is unlimited			
2b DECLASSIFICATION / DOWNGRADING SCHEDULE						
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5 MONITORING ORGANIZATION REPORT NUMBER(S)			
5a NAME OF PERFORMING ORGANIZATION Naval Postgraduate School		6b OFFICE SYMBOL (If applicable) Code 54		7a NAME OF MONITORING ORGANIZATION Naval Postgraduate School		
5c ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000				7b ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000		
8a NAME OF FUNDING / SPONSORING ORGANIZATION		8b OFFICE SYMBOL (If applicable)		9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c ADDRESS (City, State, and ZIP Code)		10 SOURCE OF FUNDING NUMBERS				
		PROGRAM ELEMENT NO		PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
11 TITLE (Include Security Classification) ESTIMATING THE RELATIONSHIPS BETWEEN THE STATE OF THE ART OF TECHNOLOGY AND PRODUCTION COST FOR U.S. AIRCRAFT						
12 PERSONAL AUTHOR(S) Lowe, Robert E.						
13a TYPE OF REPORT Master's Thesis		13b TIME COVERED FROM _____ TO _____		14 DATE OF REPORT (Year, Month, Day) 1989, June		15 PAGE COUNT 80
16 SUPPLEMENTARY NOTATION The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.						
17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)			
FIELD	GROUP	SUB-GROUP	Production Cost; Technology Measures; Reach; Stand; Advance; Regression Analysis; TACAIR Aircraft			
19 ABSTRACT (Continue on reverse if necessary and identify by block number) The primary objective of this study is to determine relationships that exist between production cost and the state of the art of technology and extensions in technology for high-technology systems. The data sample selected for study was U.S. military tactical aircraft. The central methodology used in the analysis of the aircraft data base included: 1. The development of measures for the state of the art of technology and the level of technology advance that exists within U.S. fighter and attack aircraft programs. 2. The development of measures for each aircraft program's production cost.						
20 DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS				21 ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a NAME OF RESPONSIBLE INDIVIDUAL Prof. O. Douglas Moses				22b TELEPHONE (Include Area Code) (408) 646-3218		22c OFFICE SYMBOL Code 54Md

#19 - ABSTRACT - (CONTINUED)

3. The application of various statistical procedures (regression analysis) to test specific hypotheses and build models to explain the relationships between technology and cost.

General conclusions from this study are that significant relationships do in fact exist between aircraft production cost and specific technology measures.

Approved for public release; distribution is unlimited

Estimating the Relationships Between the State of the Art of
Technology and Production Cost for U.S. Aircraft

by

Robert Edward Lowe
Lieutenant Commander, United States Naval Reserve
B.S., Purdue University, 1976

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
June 1989

1203/3
L85744
C.1

ABSTRACT

The primary objective of this study is to determine relationships that exist between production cost and the state of the art of technology and extensions in technology for high-technology systems. The data sample selected for study was U.S. military tactical aircraft.

The central methodology used in the analysis of the aircraft data base included:

1. The development of measures for the state of the art of technology and the level of technology advance that exists within U.S. fighter and attack aircraft programs.
2. The development of measures for each aircraft program's production cost.
3. The application of various statistical procedures (regression analysis) to test specific hypotheses and build models to explain the relationships between technology and cost.

General conclusions from this study are that significant relationships do in fact exist between aircraft production cost and specific technology measures.

TABLE OF CONTENTS

I.	INTRODUCTION -----	1
	A. THESIS OBJECTIVE -----	1
	B. BACKGROUND -----	2
	C. RESEARCH METHODOLOGY -----	3
	D. THESIS ORGANIZATION -----	4
II.	TECHNOLOGY MEASUREMENT -----	7
	A. TECHNOLOGY VARIABLE SELECTION -----	8
	B. DR. GREER'S TECHNOLOGY MEASUREMENT METHODOLOGY -----	9
	C. TASCFORM-AIR TECHNOLOGY MEASUREMENT METHODOLOGY -----	13
	D. SUMMARY -----	19
III.	PRODUCTION COSTS AND MEASUREMENT -----	20
	A. METHODOLOGY, PROCEDURES AND PROBLEMS -----	20
	B. SUMMARY -----	25
IV.	DATA COLLECTION -----	27
	A. TASC DATA BASE -----	27
	B. DATA SELECTION PROCEDURES -----	28
	C. SUMMARY -----	30
V.	DEVELOPING REACH, STAND AND ADVANCE TECHNOLOGY MEASURES -----	31
	A. REACH -----	31
	B. STAND -----	32
	C. ADVANCE -----	38
	D. SUMMARY -----	39

VI.	DATA ANALYSIS -----	41
	A. DEVELOPING THE HYPOTHESES -----	41
	B. DETAILED HYPOTHESES -----	42
	C. GENERAL STRATEGY -----	45
	D. TESTING HYPOTHESES ONE, TWO, THREE AND FOUR -	46
	E. OPTIMUM REGRESSION MODEL DISPLAYS -----	52
	F. CONCLUSIONS -----	52
	G. SUMMARY -----	57
VII.	CONCLUSIONS AND RECOMMENDATIONS -----	59
	A. CONCLUSIONS -----	59
	B. DATA -----	59
	C. METHODOLOGICAL REFINEMENTS -----	60
	D. CHOICE OF PREDICTOR VARIABLES -----	60
	E. HYPOTHESIS TESTING AND MODEL CONSTRUCTION ---	61
	F. RECOMMENDATIONS -----	61
	G. SUMMARY -----	63
	APPENDIX: PRODUCTION COST AND TECHNOLOGY MEASURES ----	64
	LIST OF REFERENCES -----	71
	BIBLIOGRAPHY -----	72
	INITIAL DISTRIBUTION LIST -----	73

I. INTRODUCTION

A. THESIS OBJECTIVE

The purpose of this thesis is to test for specific relationships between measures of the state of technology in complex aircraft systems and the production cost of those systems.

The benefit of this analysis is in establishing relationships between technology and cost. Knowledge of such relationships is necessary to determine future production costs for aircraft technology advances.

This thesis topic is designed as an extension of a project completed by Dr. Willis R. Greer, Jr., A Method for Estimating and Controlling the Cost of Extending Technology, Naval Postgraduate School, Monterey, CA. Dr. Greer's project analyzed the relationships between measures of technology (and technology advance) and the research and development costs for advanced satellite projects.

This study conducts an analysis similar to Dr. Greer's, but differs in two ways. First the sample consists of U.S. military tactical aircraft and their sub-systems. Second, this study emphasizes the relationships that exist between technology and production costs.

The primary purpose for testing these relationships is to develop models describing how costs are affected by extensions

in technology. These models can be used for projecting production costs as technologies advance.

Additionally, this thesis provides an understanding of what measures of technology can be created and how those measures serve to explain cost. This goal is accomplished by describing how the state of the art and advances in technology are measured.

The data base for this study was developed from selected data contained within The US Military Aircraft Cost Handbook developed by The Analytic Sciences Corporation, Arlington, Virginia.

B. BACKGROUND

This thesis, being an extension of Dr. Greer's work, capitalizes on many of the same technology measures and methodologies employed by Dr. Greer. The major difference between Dr. Greer's work and this thesis is in the methodology used to create technology measures.

Both studies utilize regression analysis techniques for testing the individual data bases to develop optimal models.

Dr. Greer used three technology measures, REACH, DESIGN and ADVANCE, to test for interrelationships between technology and cost. This study builds on the concepts introduced by Dr. Greer, but using an alternative approach, creates three technology measures, REACH, STAND and ADVANCE. Relationships

between those three measures and production cost form the central area of analysis for the study.

Dr. Greer found that his initial raw cost data for satellite systems was neither linear nor normally distributed. This thesis will report results of tests performed to determine the statistical properties of the variables used in the analysis of aircraft data sets and apply specific statistical procedures to correct any pre-existing problems.

Dr. Greer's work resulted in specific regression models which defined the relationships between satellite cost and technology measures. The major problem which detracted from the findings of his study was the lack of a larger data base. Dr. Greer only had 17 satellite systems to work with. That may have negatively impacted the performance of his models.

This thesis is based on 47 solid sets of aircraft data from which to create technology measures and 38 data sets from which to test technology cost relationships. Thirty data sets is considered the minimum for untainted data within regression analysis. Accordingly, the problem faced by Dr. Greer, was effectively eliminated for purposes of the tests performed during this thesis work.

C. RESEARCH METHODOLOGY

Two research methodologies, archival and analytical, have been utilized to select and analyze the data developed within

this thesis. The following describes how each method was used.

1. Archival Research

Archival research was employed to create a data base of measures of performance of aircraft systems. The data base was screened for consistency and included selected available data for U.S. military aircraft produced from 1950 to 1980.

Additional archival research was conducted to create a production cost data base for those aircraft selected for study. The production costs that were developed included total aircraft flyaway costs as well as specific sub-system costs.

2. Analytical Research

Analytical research was conducted to create and justify measures used to reflect aspects of technology and production costs.

Multiple hypotheses concerning technology, technology advancement, time, and production costs were developed and statistically tested.

Logic was then applied to develop descriptive models and conclusions concerning relationships between aircraft technology and production costs.

D. THESIS ORGANIZATION

Chapter II provides a detailed description of technology measurement, what the measures of technology are and how they

are derived. This task is accomplished by conducting an in-depth review of Dr. Greer's research and extending the applicable theories to a refined methodology relevant to this study.

Chapter III describes aircraft production costs and their measurement. This chapter reviews the problems and the procedures for measuring production costs and develops measurement standards to be applied to the data base.

Chapter IV discusses the data collection and selection procedures employed in developing the data base. The process describes the complexity of the initial sample selection and how consistency within the data base was developed by rejecting various observations. Following this process, the final data tables for both costs and technology within a system are presented.

Chapter V provides the procedures used in the development of the three technology measures, REACH, STAND and ADVANCE. Developing these technology measures was essential to the advancement of the central hypotheses of this study.

Chapter VI details the data analysis procedures used to test specific hypotheses. These statistical tests addressed the central research question: What relationships exist between technology and production costs? Regression models were constructed to separately address the central research question in the context of various subsets of the data base. These include three categories of aircraft:

1. All aircraft in the sample.
2. New aircraft designs.
3. New series of existing aircraft designs.

These also include four categories of cost:

1. Airframe cost.
2. Airframe plus engine cost.
3. Avionics and weapon system cost.
4. Flyaway aircraft cost.

Chapter VII presents a summary of the results, the final conclusions and recommendations.

II. TECHNOLOGY MEASUREMENT

This section will provide a detailed overview of how technology can be measured and applied to state of the art (SOA) advancement. The primary emphasis of this chapter will include a description of what technology measures are and how they are derived. In short, the concern is with methodologies for creating technology SOA measures.

The discussion of technology measurement will include a review of the study conducted by Dr. Greer based on technology extensions for the satellite industry, A Method for Estimating the Cost of Extending Technology. Dr. Greer's study and research concepts will then be compared to a separate technology measurement approach developed and applied to military aircraft by The Analytic Sciences Corporation (TASC), Arlington, VA., (the TASCFORM-AIR Model).

The calculation of technology measures and the extension of the State-of-the Art (SOA) technology are essential components to accurately developing cost models that predict Research & Development and defense program contract costs. Currently, technology measurement is a non-standardized science. This problem could adversely affect much needed defense programs which are on the leading edge of technology development.

The current system of military SOA advancement and program management includes constant financial risk and uncertainty. Industry leaders and Department of Defense (DOD) program managers do not agree on a single methodology for predicting these measures and cost. Data bases are incomplete and error filled [Ref. 1:pp. 1-6--1-8]. The failure to produce accurate measures of technology advancement has resulted in extensive cost overruns and corporate financial uncertainty, as well as program termination.

A. TECHNOLOGY VARIABLE SELECTION

Technology measurement variable selection should begin with an in-depth review of the physical characteristics and capabilities for the system under study. This phase of the research should only be conducted by researchers having in-depth technical knowledge of the system being reviewed.

The initial selection of characteristic and capability variables generally includes those factors which represent significant historical developments embodied in the state-of-the-art technology, including desired technological advances anticipated from the system design and engineering process.

For purposes of this thesis the steps in technology measurement methodology can be broken down into four broad steps:

1. Identification of the systems under study.
2. Identification of individual dimensions of technology within particular systems.

3. Combining the individual technology dimensions of interest into a single measure of SOA of technology embodied in any individual system.
4. Comparisons of the SOA measure between different systems (e.g., a predecessor system and a new system under development) or over time to create measures of the extension in the SOA of technology from one point to another. In the following discussion, these steps are reviewed as they apply to the approach adopted by Dr. Greer.

B. DR. GREER'S TECHNOLOGY MEASUREMENT METHODOLOGY

1. Step 1: Identification of Systems

Dr. Greer's study focused on satellites of all types; Navigation, Communication, Intelligence. His sample consisted of 18 satellites launched from 1966 to 1986.

2. Step 2: Identification of Technology Dimensions

Dr. Greer originally set three criteria for identifying relevant variables to reflect dimensions of technology: [Ref. 2:p. 48]

1. Variables which are generally accepted to be influenced by engineering developments.
2. Variables specified in ascending value so that the higher the technological advance the higher the SOA value.
3. Variables which are readily identifiable during the R&D phase of the systems life cycle.

Air Force satellite project management personnel rely on 85 physical characteristic variables to analyze a satellite project. With the help of subject matter experts these data fields were reduced to 18 variables relevant to describing dimensions of technology.

Dr. Greer's 18 composite variables described specific design objectives of satellite technology and eliminated those characteristics which were by-product characteristics of the design and engineering process. The selected variables reflected such properties as: launch method, design life, propellant, battery capacity, maximum temperature and nuclear hardening [Ref. 2:pp. 49-50].

Eighteen separate dimensions or variables were too many to work with (given only 18 satellite systems in the data set). Hence some procedure for reducing the number of variables was necessary. Factor analysis, a statistical procedure commonly used to identify "commonality" among individual variables, was used by Greer. The factor analysis procedure demonstrated that the variables were "clustered" into four distinct factors with 81.7% of the variance explained. These four established factors were labeled under the titles: Mission, Orbital, Electrical Power, and Environment [Ref. 2:p. 58].

Factor scores for each of the 18 satellite systems on these four factor dimensions were determined. These factor scores were then used as the four basic dimensions of technology in subsequent analysis. These factor scores can be combined in various ways to reflect the overall technology embodied in a particular system.

3. Step 3: Combining Technology Dimensions into SOA Measures

This next step relied on an innovative methodology identified by Dodson and Graver [Ref. 3:p. 39]. Using the four factor scores as basic technology variables an ellipsoid of the following form was fit to the data: [Ref. 2:p. 61]

$$\frac{X_1^2}{A_1^2} + \frac{X_2^2}{A_2^2} + \frac{X_3^2}{A_3^2} + \dots + \frac{X_n^2}{A_n^2} = 1$$

where:

X_i = Factor Scores (adjusted);

A_i = Parameters determined by the ellipsoid fitting procedure.

The result was an "average" SOA measure of "1" for the sample of satellites, represented by the four dimensional ellipsoid hypersurface. The effect of fitting the hypersurface to the data is to create SOA measures in four dimensional space which are independent of the scores of the original variables.

The level of SOA technology embodied in each satellite was then determined by inserting the factor scores for each satellite into the industry technology ellipsoid model. The technology measure for each satellite is then described as the distance from the origin to the data point and is a function of the four distinct measured scores.

4. Step 4: Create Measures of Technology Extension

A general measurement concept was then defined, called technology distance, which permits the measurement of distance between any two points within an N-dimensional space. Greer's four factor scores defined a 4-dimensional space (within which the ellipsoid surface representing the SOA of technology was fit). Using the idea of technology distance, Greer created the following measures relevant to capturing technology complexity and extension [Ref. 2:p. 78]:

1. Reach--The technological complexity of the development project.
2. Advance--The improvement or the "True" SOA progress required (from predecessor systems).
3. Redesign--The parallel movement along the old SOA plane to the desired project level (reflecting trade-offs between the four technology dimensions).

A search for statistical associations was then conducted to determine predictable technology development costs. Two factors were considered: (1) the degree to which a systems's technology was extended, and (2) the level of activity (time and cost) required to complete the extension.

Regression analysis was then used to test a "time" hypothesis resulting in the advance measure being highly significant in explaining development time. Neither edesign nor reach were statistically significant.

A second hypothesis was tested (using regression analysis) for relationships between cost and time. This hypothesis tested what happens to cost as a program is

extended beyond its scheduled completion date or is accelerated for early completion. Regression analysis demonstrated that both "natural" development time (predicted time to completion) and deviations in development time (residual time) were significant in explaining cost.

The outcome of Dr. Greer's study was a workable methodology for measuring the level of technology embodied in complex systems and relating those technology measures to development cost.

C. TASCFORM-AIR TECHNOLOGY MEASUREMENT METHODOLOGY

The TASCFORM-AIR Model data base was developed to advance theories of U.S. vs Soviet war-time mobilization capabilities and costs. This data base was reviewed and determined to be directly applicable to advancing theories on peace-time production and R&D cost relationships. The four broad steps in technology measurement as applied to the TASC data are outlined as follows.

1. Step 1: Identification of Systems

The mission organization was initially determined to be all U.S. military aircraft produced between 1950 and 1980. Due to the lack of available technological data, the scope of the project was reduced to 128 Tactical Air Community Aircraft, TACAIR¹. Ultimately, the project was again refined

¹The Tactical Air Community, TACAIR, includes two primary mission definitions; air-to-ground support (AG) and air-to-air combat support (AA). These two mission areas include: fighters, bombers, interceptors and attack helicopters.

to a data set of 91 aircraft due to incomplete historical project cost records.

2. Step 2: Identification of Technology Dimensions

The preliminary technology describing characteristics for each aircraft were collected from "Standard Aircraft Characteristics Charts" available in Jane's All The World's Aircraft (Franklin Watts, Inc., et. al., 1954-1980). The physical characteristics included the following data: [Ref. 4:p. II-5]

1. Manufacturer.
2. Wing Type (Fixed/Rotary).
3. Aircraft Type.
 - a. CTOL--Conventional Takeoff and Landing;
 - b. VSTOL--Vertical/Short Takeoff and Landing;
 - c. STOL--Short Takeoff and Landing;
4. Engine Designator.
5. Number of Engines.
6. Branch of Service.

Eight airframe/propulsion variables and 11 weapons system and avionics variables were also collected to address specific aircraft technology characteristics. Select DOD subject matter experts made the determination as to which technology variables best represented aircraft design and engineering features desired in military aircraft.

Note: some aircraft models have multi-mission capabilities and combat roles.

Two figure of merit data base tables were then constructed to describe technology measures for the TASCFORM-AIR Model: [Ref. 4:p. III-1]

1. TASCFORM-AIR Airframe Performance (AP).
2. TASCFORM-AIR Aircraft System Performance (ASP).

These two TASCFORM-AIR Model SOA technology data bases are the central core for this study of technology measurement. In order to best understand what the AP and ASP figure of merit calculations represent, a review of their development methodology is necessary.

All TASCFORM-AIR Models use basic airframe/propulsion characteristics normalized relative to a baseline aircraft, the F-4B, as the basis for the figure of merit.

Airframe/propulsion characteristics include the following variables: [Ref. 1:pp. 2-6, 2-7]

1. Payload (PL) expressed in pounds of stored station capacity plus weight of any gun and ammunition carried in ground attack, and in number of air-to-air ordnance stations, including 1 for an internal gun, in air-to-air combat.
2. Range, including enhanced responsiveness conferred by V/STOL and STOL basing modes (R+BF) maximum range for a clean aircraft, using internal fuel only to fly a Mil-C profile², with an additional basing factor of 500 nautical miles (NM) for VTOL capability, 250 NM for STOL capability, and 100 NM for CTOL or V/STOL carrier capability.

²Mil-C Profile refers to an early 1980's flight performance description for USAF & USN tacair aircraft. It was used to describe a combination of high altitude vs low altitude enroute flight plans for various mission profiles.

3. Maneuverability (M) expressed in terms of its ability to change direction, altitude, or airspeed, represented by maximum specific power for fixed-wing aircraft.
4. Useful Speed (V) expressed as maximum indicated airspeed in knots, at sea level, in the air-to-ground roles, and as best mach, at all altitudes, in the air-to-air role.

3. Step 3: Combining Technology Dimensions into SOA Measures

Aircraft performance values were expressed as a function of each variable: [Ref. 1:pp. 2-6, 2-7]

$$AP = f(PL, R+BF, M, V)$$

Specific weighted values were applied to each variable by a conference committee of select DOD subject matter experts (operationally-experienced aviators). These weighted values were based on judgmental comparisons of the relative importance of each system characteristic as it contributes to one of the specific tacair roles. The weighting values received extensive review and modification by all branches of the military, reflecting a balance of desired characteristics as they applied to each branch and their unique combat operating environment. This weighting process corresponds to real world operational methodology wh determining how to employ each multi-mission aircraft.

Each value was then divided by the corresponding baseline category value for the F-4B. This provided the

comparative basis for each aircraft's figures of merit [Ref. 1:p. 2-8].

The airframe performance figures of merit were then transformed into an additive expression vice a multiplicative function. The mathematical expression for the AP mission oriented figures of merit became: [Ref. 1:p. 2-9]

$$AP = F(PL)*PL + F(R)*(R+BF) + F(M)*M + F(V)*V$$

where F(PL), F(R), F(M), and F(V) represent the judgmental weights.

Aircraft System Performance (ASP), the second major TASCFORM-AIR SOA technology measure, was derived by additionally accounting for weapons and avionics characteristics employed by each aircraft. These calculations reflect the tactical impact each system has on airframe/propulsion performance when expressed as a function of the AP figure of merit.

Three "master" weapons system and avionic variables were used to modify the AP equation. These variables were: [Ref. 1:pp. 2-13--2-28]

1. Payload Utility (PU) a payload modifier, adapts the performance measure to target acquisition and engagement capabilities. For specific information on how PU was calculated refer to The TASCFORM-AIR Model, TR-1334-3.
2. Navigation Coefficient (NAV) modifies the range capability by rating various internal navigation systems as either poor, good, or excellent.

3. Survivability Factor (S), a variable of major significance, modifies all variables. It is defined as a susceptibility to detection, identification, and lock-on tracking and reflects the probability of being destroyed once hit by hostile fire.

The application of the aircraft system performance variables to the AP equation produces the ASP technology measurement: [Ref. 1:p. 2-16]

$$ASP = (F(PL)*PL*PU + F(R)*(R +BF)*NAV + F(M)*M + F(V)*V) * S$$

Like the AP measure, ASP has been normalized to the F-4B baseline aircraft and produces a decisive figure of merit rating system for each aircraft studied.

4. Step 4: Creating Measures of Technology Extension

The major technology measurement concept difference, between Dr. Greer's study and this study, is that the TASCFORM-AIR Model utilizes a single axis/dimension figure of merit to describe technology, vice the four axis ellipsoid model used by Dr. Greer. The use of a single axis/dimension figure of merit can be used to reflect the essence of Dr. Greer's technology extension measurement concepts, except for the redesign feature. The advance and reach concepts are applicable to this study and will be fully explored in Chapter V.

D. SUMMARY

This portion of the study shows the complexity of technology measurement. It reviewed the necessary steps in creating measures to reflect the SOA of technology and extensions in technology. It reviewed the specific steps used to create SOA measures for the aircraft that will be studied.

The specific aircraft performance and aircraft system performance data base figures of merit utilized for this study are available in the Appendix.

The remainder of this study will focus on a methodology for applying the TASCFORM-AIR technology measures and data base figures of merit. This will be accomplished by advancing theories on relationships between aircraft production costs and the extension of technology in aircraft.

III. PRODUCTION COSTS AND MEASUREMENT

This chapter will describe the methodologies and procedures for measuring production costs. The primary objective is to provide a consistent set of cost measures that when related to the TASCFORM-Air model aircraft performance measures, can be used to test for relationships that may exist between technology and aircraft system cost. All aircraft cost data were taken from the US Military Aircraft Cost Handbook [Ref. 5].

This chapter first reviews the collection and adjustment procedures used in creating the basic cost data contained in the US Military Aircraft Cost Handbook (Steps 1-3, to follow). The chapter concludes (Step 4) by describing the development of the specific cost measures that will be used in later analysis.

A. METHODOLOGY, PROCEDURES AND PROBLEMS

1. Step 1. Data Collection

The cost data for the aircraft contained within this study was generated by the Air Force and Navy from each service's historical data files. The cost information was provided on the basis of each Mission/Design/Series aircraft and included: [Ref. 5:p. II-7]

1. The total procurement quantities by specific annual fiscal year.

2. The total flyaway costs or total obligational authority (TOA) in specific then year dollars.
3. A breakdown of total flyaway costs for each aircraft by the major categories of:
 - a. Airframe;
 - b. Engines;
 - c. Electronics;
 - d. Armament;
 - e. Other.

2. Step 2. Develop Consistency within the Data Set

In order to use the data appropriately in any future tests, the data had to first be evaluated for completeness and consistency.

Not all the data collected in step 1 could be fully utilized. The Department of Defense (DOD) historical cost data files contained multiple inconsistencies, such as lack of uniformity within the Research & Development cost records. Additionally, DOD standards did not exist for the determination of aircraft system modification and conversion costs. Therefore, these cost data items were eliminated from the data base [Ref. 4:p. II-7].

Cost reporting standards within each service changed over time in compliance with specific DOD management objectives. This caused variations in the historical cost data which required extensive review and some adjustments. Since 1970, DOD cost reporting standards have been refined, resulting in more precise historical cost data. The in-depth

review of the pre-1970 data produced the following adjustments: [Ref. 4:pp. II-7--II-12]

1. The primary area of concern for the reporting standards was nonrecurring costs. Initial tooling was listed as Research Development Test and Evaluation (RDT&E) for some DOD aircraft, while other aircraft programs listed it as production cost. The Air Force data had three aircraft data sets where nonrecurring costs were reported separately, the A-10A, F-15A, F-16A. This problem was also evident in the post 1969 Navy data. After 1969, all Navy data files began listing nonrecurring cost separately. To promote consistency within the entire data base, nonrecurring costs were included in the total flyaway costs for all aircraft.
2. The second area of concern was the individual inconsistencies which existed within each service's data. The following minor deviations were noted:
 - a. During FY51-FY55, the Navy only reported unit costs and total number of aircraft produced. This required the unit cost to be multiplied by the number of aircraft to develop the subsystem and total flyaway costs for that period.
 - b. Seven Air Force aircraft data sets were incomplete with respect to the breakout of major subsystem costs. These aircraft are F-105D&F, F-111A/D&E, FB-111A and the F-4C.
 - c. Missing historical cost data for some aircraft resulted in missing cost measures.

These adjustments provided a relative consistency among the total flyaway cost data and the subsystem costs.

3. Step 3. Inflation Indexing

Once the consistent categories of cost data were established, the historical cost data had to be adjusted from individual then-year dollars to constant dollars.

An inflation escalation index provided by the Office of Assistant Secretary of Defense, Comptroller, was applied to

the cost data base [Ref. 4:pp. III-1--III-7]. This procedure "normalized" the cost figures and produced cost figures inflation-adjusted to the base year, FY1981. The end results are relative cost figures that can be computed across aircraft much the same as the performance "figures of merit."

4. Step 4. Developing Cost Measures

After the consistency adjustments and inflation indexing procedures were conducted, the available raw data consisted of cost and quantities per lot for each aircraft. Comparisons of cost per lot or average cost per lot across aircraft systems was deemed to be inappropriate for this study because:

1. Production lots consisted of different quantities, and
2. Cost reduction occurs due to a number of factors, but typically within the aircraft industry as more lots are produced the "learning curve" reduces average cost per lot.

It was decided to create a single average cost figure at a consistent quantity point which would reflect the cost reduction that occurs due to learning. The following procedures were conducted to arrive at a cumulative average cost (CAC) of producing 100 units: [Ref. 4:pp. III-7--III-16]

1. Cumulative quantities at the end of each lot were determined by summing the quantities in all preceding lots.
2. Cumulative average costs (FY81) at the end of each lot were determined by summing the costs of all preceding lots and divided by the cumulative quantities.
3. Learning curves were then developed and fit to the cumulative average costs and quantities. Regression

analysis procedures were used resulting in the following cumulative average cost curve equation:

$$C_Q = A Q^B$$

where:

C_Q = Cumulative average cost for a quantity Q .

A = Constant, the first unit cost (estimated by the fitting procedure).

Q = Cumulative quantity.

B = Constant, the slope or learning rate.
(Estimated by the fitting procedure.)

4. The cumulative average cost of 100 units, CAC (100), was determined by setting Q at 100 and re-entering the learning curve to solve for C_Q .

The methodology employed is unique but provides for comparable average cost figures at a comparable quantity for all aircraft. The primary consideration is the different learning rates experienced on individual aircraft programs.

This methodology was conducted on three separate cost series: airframe costs, airframe plus engine costs and total flyaway costs, and four variables resulted:

1. CACF--CAC (100 units), airframe.
2. CACE--CAC (100 units), airframe plus engines.
3. CACA--CAC (100 units), flyaway.
4. CACS--CAC (100 units), avionics plus weapons systems, calculated as: CACA - CACE.

B. SUMMARY

When dealing with cost and performance measures, one must realize that both are related to the quantity or lot size of the aircraft produced. Aircraft are not purchased singly but, rather in lots of varying quantities. Generally, investment and production costs are lower per unit for large production lots than for low outputs such as experimental or RDT&E aircraft.

This chapter discussed the effects of learning curves on aircraft cost data. Performance measure variables also improve as the production learning curve improves. The larger the lot size, the more reliable the performance measures become. This standard is attributed to improved production techniques developed over the production cycle and system reliability generated from modifications incorporated during production. Simplistically stated, aircraft models of small lot size have no opportunity for redesign or modification due to the limited production cycle time. Large lot aircraft production cycles have more opportunities through time to incorporate production modifications that enhance the performance measures of the original design. This study includes the effects of production modifications and their costs.

One limitation of this study is the absence of explicit consideration of the effects of external production factors,

such as after delivery modifications to aircraft systems, on production cost.

Most aircraft models and subsystems undergo extensive modification and update throughout their life cycles. External research has shown that some aircraft subsystems receive after delivery performance improvements and modifications that more than triple their capabilities. Both the cost and effect of after production modifications have significance when including their impact on the advance of the SOA within the industry.

The uninformed reader may wrongly conclude that the average unit flyaway cost or subsystem cost are only related to prior industry design production costs. In reality, average unit flyaway cost and subsystem costs are affected by many external factors. Further research is recommended to determine what external production factors exists within the aircraft industry and what effect they have on advancing SOA cost relationships.

The specific tests for relationships between the cost measures and the performance measures will be fully explored in Chapter V. The cost measure data fields can be found in the Appendix.

IV. DATA COLLECTION

This chapter will describe the sample selection and data collection procedures for creating this study's aircraft data base. The selection process will list the systems to be included in the analysis and describe what systems were rejected and why. From the selection process, data presentation tables for both costs and technology within an aircraft system will be developed.

The original scope of this study was all US military aircraft. Due to scope restrictions and limited availability of data, the US Military Cost Handbook [Ref. 5], was selected as the primary source document for selecting a sample of aircraft and developing a data base of aircraft costs and performance measures.

A. TASC DATA BASE

The cost handbook contains a broad-based, but not all inclusive sample of 108 data sets of US TACAIR aircraft that were produced from 1950 to 1980. This study was conducted by The Analytic Sciences Corporation (TASC) under a Department of Defense, Office of Net Assessment, contract. The study explored cost vs performance relationships for the mobilization of U.S. forces during a theoretical national emergency with the Soviet Union. The TASC study contains

extensive data on aircraft performance and cost. These factors were considered ideal for advancing this study's research questions.

All 108 aircraft data sets were identified by mission (fighter, attack, bomber, patrol, etc.), design, and series (e.g., B-52C, F-14A, A-7D). Where successive series of a particular aircraft design resulted in virtually indistinguishable aircraft, the handbook combines different series aircraft into a single combined series (e.g., A-7A, A-7B became A-7A/B) and additionally provides a data set for the combined series. Data for 48 individual aircraft were combined into 20 separate multiple-series data sets, resulting in a total of 128 data sets available.

B. DATA SELECTION PROCEDURES

It was determined that the TASC's sample of 128 data sets could be reduced to eliminate repetitive data and tactical aircraft of dissimilar characteristics, mission and flight profiles. The following methodology was employed to reduce the sample.

The 20 "multiple-series" data sets were analyzed and determined to be complete; they adequately included all the desired performance and cost measures. To eliminate the duplication of data, the 20 "multiple-series" sets were retained. The 48 individual aircraft data sets included in the "multiple-series" data, were dropped from this study's

data base. This procedure reduced the number of distinct aircraft programs to 80.

Performance characteristics and mission profiles were then analyzed to ensure consistency within the data base with respect to the performance measures. To be more specific, the performance measures used in this study rely on the F-4B as a baseline aircraft. It was decided that the performance measures for aircraft would be most valid and most comparable if all aircraft in the sample had:

1. Similar missions descriptions as the F-4B.
2. Similar operating characteristics as the F-4B. This idea lead to deletion of additional aircraft data sets as follows.

Mission profile was used to eliminate dissimilar aircraft data sets. Since the F-4B was a dual mission aircraft (fighter and attack) aircraft serving all other mission profiles were eliminated. This procedure resulted in eliminating 19 individual aircraft data sets (strategic bombers and patrol aircraft) and reduced the number of distinct aircraft programs to 61.

Performance and flight profile relationships were then evaluated relative to the F-4B to eliminate dissimilar aircraft data sets. The F-4B being a conventional takeoff-and-landing flight profile aircraft (CTOL) was determined to be important. Performance and technology characteristics are directly related to the individual aircraft's takeoff-and-landing flight profile. This analysis resulted in eliminating

one short field takeoff-and-landing aircraft (STOL) and five vertical takeoff-and-landing aircraft (VTOL). Fifty-five distinct aircraft programs remained.

The last adjustment to the data base was centered on the relationships between successive series of aircraft and specific advances in technology incorporated within each successive series of the aircraft produced. Some later series of aircraft models demonstrated significant advances in technology, while others demonstrated no extension in technology. Where a later series of a particular aircraft model showed no incremental change in technology over a preceding one, the later series was eliminated. This procedure eliminated eight data sets.

C. SUMMARY

This methodology of data selection and sample reduction resulted in the selection of 47 distinct aircraft data sets. All aircraft were consistent with respect to performance, mission (fighter and attack) and flight profile (CTOL). Additionally, each aircraft selected provided significant advances in technology over previous models or series during the 1950 to 1980 time period. A list of the 47 aircraft programs that comprise the final sample for this study is contained in the Appendix.

V. DEVELOPING REACH, STAND AND ADVANCE TECHNOLOGY MEASURES

This chapter will describe the procedures used in the development of three measures of technology: REACH, STAND and ADVANCE. These technology measures will be employed in the analysis of cost in Chapter VI of this thesis.

This section will first provide conceptual definitions of the three measures, REACH, STAND and ADVANCE, followed by the procedures used to create the measures. Each of the three measures are designed to reflect some aspect of technology embodied in a system and each will be developed for three different components of the aircraft. More specifically, the technology performance measures will be developed for:

1. Aircraft PLATFORM (aircraft frame plus engine).
2. Flyaway AIRCRAFT (platform plus systems).
3. Aircraft Avionics and Weapon SYSTEMS.

Alternative approaches to creating measures of STAND and ADVANCE will also be discussed.

A. REACH

REACH is a measure of the total technology embodied in a system. Technology can be measured using data describing the "engineering" sophistication of a system (an input measure) or using data describing the performance of a system (an output measure). Chapter II discussed measures of aircraft system

performance and those measures are used here as measures of REACH. Three specific measures of REACH, for the three components of the aircraft, are defined as follows:

1. PLATFORM REACH = AP (Airframe performance from Chapter II).
2. FLYAWAY REACH = ASP (Flyaway system performance from Chapter II).
3. SYSTEMS REACH = ASP/AP.

The measure of SYSTEMS REACH is a constructed measure, designed to capture the performance enhancement achieved by adding weapons and avionics systems to an aircraft platform (resulting in the flyaway aircraft). This constructed measure assumes that flyaway aircraft performance is a multiplicative function of platform performance and, avionics and weapons systems' performance:

$$\text{FLYAWAY REACH} = \text{PLATFORM REACH} \times \text{SYSTEMS REACH}.$$

B. STAND

STAND is defined as the state of the art of technology in existence at the time a particular aircraft is first produced. Hence, STAND measures where technology "stands" at the time a new aircraft is created. STAND provides a reference point for determining whether new aircraft represent extensions in the existing state of the art.

1. Time Trend Approach

Two alternative approaches exist for determining (and operationally defining) measures of STAND. The first alternative defines STAND as the trend in the state of the art of technology over time. A trend line was developed by fitting a regression equation to the various REACH measures defined above. Thus, STAND can be conceived of as the "expected" REACH of an aircraft, as a function of time. The specific procedures were as follows.

Step 1. The REACH technology measures (PLATFORM, FLYAWAY and SYSTEM) were regressed separately against the START YEAR¹ for each aircraft program. The REACH figures of merit were designated as the dependent variable and program START YEAR was designated the independent variable.

Step 2. Analysis of the regressions resulted in the determination that the start year variable was highly significant and produced a tight fitting model which could well explain the variation over time in REACH. Additionally, the models were tested for linearity and normal distribution with no exceptions noted.

The regression analysis produced the following regression equations and data analysis. Additionally, time trends can be observed graphically. The corresponding plot diagrams

¹START YEAR is defined as the first year a program is in actual production. START YEAR data was obtained from the TASC data base.

show plots of PLATFORM TECH, SYSTEMS TECH and FLYAWAY TECH vs TIME. Figures 1-3 confirm the conclusions from the regression analysis that strong relationships exist between TECH and TIME:

Step 3. The original start year data were then reinserted back into each regression equation to determine a predicted value for REACH at a given start year. These predicted values represent the state of the art of technology as reflected by the time trend line at a given start year. In short, these predicted values measure where technology stands at a given year. To summarize, measures of STAND were operationally defined as follows:

1. PLATFORM STAND (R) = Predicted PLATFORM REACH from regression equation.
2. SYSTEM STAND (R) = Predicted SYSTEM REACH from regression equation.
3. FLYAWAY STAND (R) = Predicted FLYAWAY REACH from regression equation.

Note: The (R) indicates that these measures of STAND are based on the time regression approach.

2. Predecessor Aircraft Approach

The second alternative defines STAND in relation to the highest level of REACH achieved (all predecessor systems considered) prior to the start of the current aircraft program. This prior performance definition of STAND was calculated as follows.

$$\text{PLATFORM REACH} = -8.61954 + 0.2971630(\text{START YEAR})$$

	T-RATIO	P-TEST
CONSTANT	-3.39	0.001
STARTYR	7.01	0.000

STANDARD DEVIATION = 2.406
 ADJUSTED R-SQUARED = 51.1%
 F-TEST = 49.16
 CORRELATION = 0.723

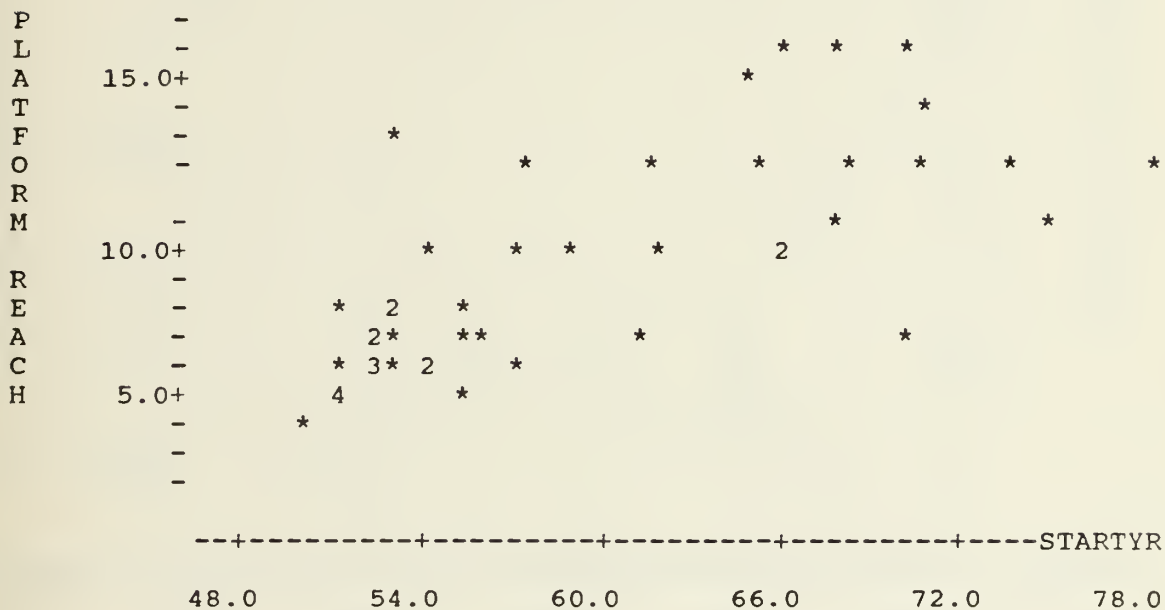


Figure 1. Platform REACH vs STARTYR

$$\text{FLYAWAY REACH} = -30.94290 + 0.7906258(\text{START YEAR})$$

	T-RATIO	P-TEST
CONSTANT	-6.12	0.000
STARTYR	8.39	0.000

STANDARD DEVIATION = 4.780

ADJUSTED R-SQUARED = 60.1%

F-TEST = 70.32

CORRELATION = 0.781

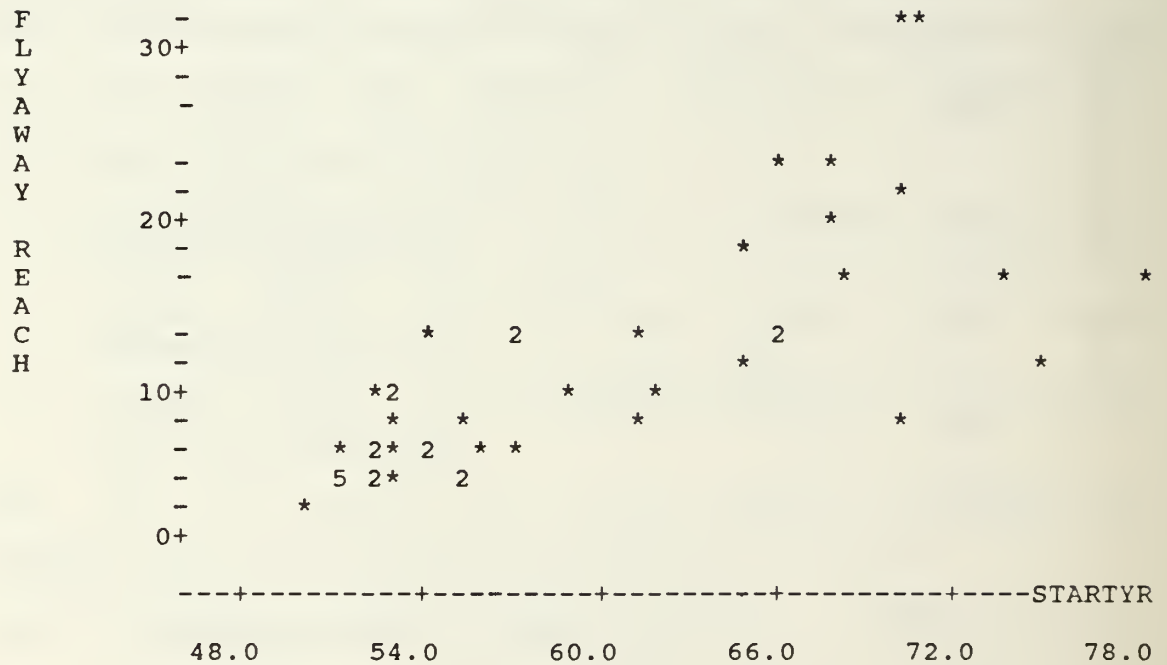


Figure 2. Flyaway REACH vs STARTYR

Step 1. The REACH performance measures were sorted by program start year in ascending order from 1950 to 1978.

Step 2. Individual observations were made of all programs that preceded the current or selected aircraft program.

Step 3. The highest level of REACH performance that had been achieved prior to the commencement of the program under consideration was selected and defined to be the relevant measure of where the state of the art of technology stood at the commencement of the new program under consideration.

This procedure was applied to each of the these kinds of technology measures resulting in the following:

1. PLATFORM STAND (P) = highest predecessor PLATFORM REACH.
2. SYSTEM STAND (P) = highest predecessor SYSTEM REACH.
3. FLYAWAY STAND (P) = highest predecessor FLYAWAY REACH.

Note: The (P) designates that these measures of STAND were based on the predecessor aircraft approach.

C. ADVANCE

ADVANCE is defined as the extension in technology beyond the current state of the art. For any individual aircraft, ADVANCE equals the difference between the technology in the particular aircraft and the state of the art of technology

when the aircraft was produced. In short, $ADVANCE = REACH - STAND$. Since two approaches to measuring STAND were used, two alternative measures of ADVANCE result:

1. The deviation from the time trend line.
2. The difference between the actual REACH of the system and the prior highest level of REACH achieved.

The measures of ADVANCE were created using two mathematical equations provided below:

1. $ADVANCE (R) = REACH \text{ minus } STAND (R)$, derived from the regression time trend.
2. $ADVANCE (P) = REACH \text{ minus } STAND (P)$, the highest level of REACH achieved prior to the start of the current aircraft.

These procedures for calculating ADVANCE produced six distinct variables.

1. PLATFORM ADVANCE (R).
2. FLYAWAY ADVANCE (R).
3. SYSTEM ADVANCE (R).
4. PLATFORM ADVANCE (P).
5. FLYAWAY ADVANCE (P).
6. SYSTEM ADVANCE (P).

D. SUMMARY

This chapter has described the procedures used to create three distinct technology measures for each aircraft: REACH, STAND and ADVANCE.

Each of these technology measures were calculated for each of three components of aircraft: PLATFORM, SYSTEMS and FLYAWAY.

ADVANCE and STAND were derived from simple measures of REACH and REACH measures were defined by, or created by transformations of the performance figures of merit (AP and ASP) developed by TASC. Hence, all of the technology measures rest on the TASC methodology.

Refer to the Appendix for the values of each technology measure referenced in this chapter.

VI. DATA ANALYSIS

This chapter describes the procedures used in the testing for, and the analysis of, relationships which exist between production cost and the state of the art in technology for aircraft systems. These relationships are tested and analyzed using a series of simple and multiple regression techniques outlined in a manuscript by Dr. S.S. Liao (unpublished manuscript, Naval Postgraduate School, Monterey, CA).

A. DEVELOPING THE HYPOTHESES

Four hypotheses were developed which describe the expected relationships between technology and cost.

The three hypotheses which are general in nature include:

1. H_1 : Production cost = $+f(\text{REACH})$
(Production cost is expected to increase with the degree of technological complexity of the aircraft project.)
2. H_2 : Production cost = $+f(\text{STAND})$
(STAND reflects the average state of the art of technology at the time an individual aircraft was produced. Cost is expected to increase as technology on average becomes more complex.)
3. H_3 : Production cost = $+f(\text{ADVANCE})$
(Production cost is expected to increase with the degree of technological extension of the program.)

The final hypothesis developed was a control hypothesis which tested the difference in production cost between new aircraft designs and follow-on series of existing aircraft designs. Since production costs are expected to be higher for

new designs than for follow-on series, tests need to be developed which verify this hypothesis.

4. H_4 : Production cost = +f(First Series of a New Design) (Production learning, which occurs in the first series of a new aircraft design, results in lower production cost in follow-on aircraft series. Hence, production cost is expected to be greater for new designs.)

B. DETAILED HYPOTHESES

In order to apply regression analysis to the four hypotheses, each of the dependent and independent variables needed to be established.

The four dependent variables were derived from the cost measures and were described in Chapter IV. These four variables include:

1. AIRFRAME COST.
2. PLATFORM COST.
3. SYSTEM COST.
4. FLYAWAY COST.

For brevity, this thesis will use the general term "COST" to refer to the four costs.

The three independent variables were derived from the technology measures established in Chapter V. These three variables include:

1. REACH.
2. STAND.
3. ADVANCE.

Note: Two alternative approaches to creating measures of STAND and ADVANCE were detailed in Chapter V: The regression (R) approach and the predecessor (P) approach. Tests were performed using both kinds of STAND and ADVANCE measures. R-type measures proved to be more significant during single variable regression testing. The P-type measures were determined to be insignificant in the single variable regression analysis. During the multiple regression testing phase, both R and P type measures were significant, but the R-type provided the highest significance levels. Given these findings, measures of STAND and ADVANCE based on regression approach were deemed to be superior. The analysis discussed in the following sections was conducted using R-type STAND and ADVANCE measures.

To clarify the discussion, this study will use the following general terms to refer to the independent variables:

1. REACH to refer to the three measures of the technological complexity existing within a project.
2. STAND to refer to the three measures of the state of the art of technology at the time of program production.
3. ADVANCE to refer to the three measures of the technology extension which exists within a program.

In order to thoroughly test hypotheses one, two and three, the following regression models were constructed and tested:

1. PLATFORM COST = +f(PLATFORM REACH)
 = +f(PLATFORM STAND)
 = +f(PLATFORM ADVANCE)
 = +f(PLATFORM REACH, PLATFORM STAND)
 = +f(PLATFORM REACH, PLATFORM ADVANCE)
 = +f(PLATFORM STAND, PLATFORM ADVANCE)

2. SYSTEM COST = +f(SYSTEM REACH)
 = +f(SYSTEM STAND)
 = +f(SYSTEM ADVANCE)
 = +f(SYSTEM REACH, SYSTEM STAND)
 = +f(SYSTEM REACH, SYSTEM ADVANCE)
 = +f(SYSTEM STAND, SYSTEM ADVANCE)

3. FLYAWAY COST = +f(FLYAWAY REACH)
 = +f(FLYAWAY STAND)
 = +f(FLYAWAY ADVANCE)
 = +f(FLYAWAY REACH, FLYAWAY STAND)
 = +f(FLYAWAY REACH, FLYAWAY ADVANCE)
 = +f(FLYAWAY STAND, FLYAWAY ADVANCE)

4. AIRFRAME COST was the only cost measure which had no corresponding REACH, STAND or ADVANCE technology measure associated with it. This was a direct consequence of the TASC research data; no AIRFRAME REACH measure was provided within the TASC methodology therefore, AIRFRAME STAND and AIRFRAME ADVANCE could not be developed.

To solve this problem, this study evaluated the available REACH measures and determined that PLATFORM REACH provided the performance measure with the closest association with AIRFRAME COST. (All AIRFRAME COST models were tested using PLATFORM REACH, PLATFORM STAND and PLATFORM ADVANCE.)

The regression models developed for AIRFRAME COST included:

1. AIRFRAME COST = +f(PLATFORM REACH)
 = +f(PLATFORM STAND)
 = +f(PLATFORM ADVANCE)
 = +f(PLATFORM REACH, PLATFORM STAND)
 = +f(PLATFORM REACH, PLATFORM ADVANCE)
 = +f(PLATFORM STAND, PLATFORM ADVANCE)

C. GENERAL STRATEGY

The following steps were employed as a general strategy for testing the four central hypotheses.

Step 1. Observe the data to identify existing statistical problems with each dependent and independent variable. This task entailed two procedures:

1. Histograms were generated to test the variables for normal distribution. This procedure produced normal distribution plots skewed to the left (higher cost) for the COST data.
2. Plots of each variable against the STARTYR resulted in determinations that all the variables were linear, as desired, but the COST variable plots indicated that residuals were heteroscedatic (of non-constant variance).

Step 2. Since two problems were noted with the COST variables, regression transformation procedures needed to be applied to transform the COST data to ensure a well defined or "tight" fitting regression model. The objective in transforming the dependent COST variable is to simultaneously "shrink" the effect of the skewed larger COST measures (i.e., normalize the variables) and correct the undesirable impact of non-constant variance on the regressions.

Three regression transformation procedures were attempted:

1. Natural logs were applied to COST. [$\log(\text{COST})$]
2. The square roots of COST were calculated. [$\sqrt{\text{COST}}$]
3. The reciprocals of COST were calculated. [$1/\text{COST}$]

The $\log(\text{COST})$ regression transformation procedure produced the tightest "shrinking" effect on the data, while $(1/\text{COST})$ produced the smallest "shrinking" effect.

Each of the three transformations of the COST variables were again checked for normal distribution and non-constant variance. The $\log(\text{COST})$ transformation corrected both problems and was selected to replace COST as the dependent variable in the regressions testing the central hypotheses.

Step 3. This involved testing the data base to observe the relationships between $\log(\text{COST})$ and the independent variables. This step is considered the core of the analysis of the four central hypotheses of this study.

D. TESTING HYPOTHESES ONE, TWO, THREE AND FOUR

Three of the hypotheses of this study are directed towards determining the relationships of REACH, STAND and ADVANCE to production costs. Testing each of the variables both singularly and through multiple regression establishes a comparative basis from which to select the optimum models.

In order to test hypothesis four, a "dummy" variable, SERIES, was introduced as an independent variable for inclusion in the various COST regression models. SERIES was added to each regression model to form distinctly new regression models. The SERIES variable was essential to the testing of hypothesis four because it provided a means to

designate which programs were new production programs and which programs were follow-on production programs.

The "dummy" SERIES variable was coded as follows:

1. Initial series aircraft (first series of a new design; i.e., A-7A) were designated with a zero.
2. Follow-on series aircraft (later series aircraft of an existing design; i.e., A-7E) were designated with a one.

Given this coding for SERIES, the hypothesis calls for a negative relationship between COST and SERIES; follow-on series aircraft should cost less.

The testing of the four hypotheses was completed in four phases of analysis. The four phases of analysis included the following.

1. Phase One

Phase one was designed to test the simple regression models (models including only one independent variable). This procedure ensured that all the dependent $\log(\text{COST})$ variables in combination with the individual technology variables were linear, normally distributed, possessed no variance problems, and that regression residuals were independent.

The test for linearity in regression analysis ensures that the independent variables do not need to be adjusted through regression transformation. This procedure was completed by plotting the independent technology measures against STARTYR. All independent variables were determined to be linear.

The normal distribution was checked by the use of histogram plots. All independent variables were normally distributed.

The variance was checked by viewing the plots during the linearity check for constant variance or non-constant (expanding or collapsing) variance. This procedure resulted in the finding that all independent variables exhibited a constant variance.

The models regressing $\log(\text{COST})$ independently on REACH, STAND, ADVANCE were tested for independence of residuals by the use of the Durbin-Watson test statistic. Each regression model produced Durbin-Watson statistics which indicated no strong relationship among residuals. This indicates that the residuals were independent of the $\log(\text{COST})$ measures and no adjustments to the data were needed.

At this point, all regression models were analyzed for significance prior to further testing to eliminate redundant variables.

STAND was found to be significant as a predictor of $\log(\text{COST})$. R-squared (adjusted) values ranged from 38.5 to 45.3%. All T-ratios and P-tests were evaluated as significant. Additionally, the F-tests were significant, ranging from 14.1 to 23.8. This provided some initial evidence in support of hypothesis two.

ADVANCE was found to be a significant and valid predictor of $\log(\text{COST})$. R-squared (adjusted) values ranged

from 18.6 to 20.9%. The T-ratios were significant and the F-test ranged from 7.18 to 10.75. This provided some initial evidence in support of hypothesis three.

REACH was found to be a significant predictor of $\log(\text{COST})$. The R-squared (adjusted) values ranged from 46.2 to 62.3%. The fact that the regression models resulted in high significance levels demonstrated hypothesis one was valid. But, further analysis of the REACH models indicated that REACH provided no additional information useful for explaining production cost beyond that contained in STAND and ADVANCE. This is because REACH is a direct linear combination of STAND and ADVANCE and is considered a redundant measure. Due to this finding REACH was eliminated from further testing.

2. Phase Two

This phase required the use of multiple regression testing, where SERIES (independent variable) was added to the $\log(\text{COST})$ models with either STAND or ADVANCE. (For example, $\text{SYSTEM COST} = f(\text{SYSTEM STAND}, \text{SERIES})$; $\text{SYSTEM COST} = f(\text{SYSTEM ADVANCE}, \text{SERIES})$; ...; etc.) The objective here was to provide an initial test of hypothesis four and to observe the effect on the relationship between COST and STAND or ADVANCE with SERIES controlled.

Multiple regression testing of STAND and ADVANCE in combination with SERIES produced models with improved significance. R-squared values improved by 8-18% along with improved T-ratios and P-tests. All models were evaluated and

determined to be highly significant, the residuals were normally distributed and the models explained a large proportion of the variance in production cost. R-squared (adjusted) values ranged from 28.4 to 61.1%. This phase of study provided an initial indication that hypothesis four was valid.

3. Phase Three

Phase three introduced the concept of testing STAND and ADVANCE together in multiple regression analysis modeling. The objective here was to determine if the joint explanatory ability of the two technology measures lead to improved predictions of COST. Four models were tested during this phase:

1. $\log(\text{AIRFRAME COST}) = +f(\text{PLATFORM STAND}, \text{PLATFORM ADVANCE})^1.$
2. $\log(\text{PLATFORM COST}) = +f(\text{PLATFORM STAND}, \text{PLATFORM ADVANCE}).$
3. $\log(\text{SYSTEM COST}) = +f(\text{SYSTEM STAND}, \text{SYSTEM ADVANCE}).$
4. $\log(\text{FLYAWAY COST}) = +f(\text{FLYAWAY STAND}, \text{FLYAWAY ADVANCE}).$

When analyzed, these regression models consistently demonstrated positive coefficients for STAND and ADVANCE, highly significant T-ratios, and F-tests, along with strong improvements to the R-squared values. R-squared (adjusted) ranged from 48.3 to 66.9%.

¹Recall that no AIRFRAME REACH measure was provided and therefore, PLATFORM REACH was substituted as the technology measure with the closest association to AIRFRAME REACH.

These results provided the basis for concluding hypotheses two and three were valid. Production cost does increase with improvements in the state of the art in technology and the degree of technological extension within a program.

4. Phase Four

Phase four represented the re-introduction of the SERIES variable to the phase three regressions. The purpose here was threefold: First, to determine if the results found for STAND and ADVANCE in the phase three regressions continued to hold when SERIES was controlled. Second, to provide a re-test of hypothesis four in conjunction with more complete models. Third, to determine if R-squared (adjusted) of the models could be improved. The significance of each $\log(\text{COST})$ model improved with regards to T-ratios, P-tests and F-tests. Additionally, R-squared improved 3-7% depending on the specific model.

The coefficients for STAND, ADVANCE and SERIES were significant, with the hypothesized signs, in each of the models (with the exception of SERIES in the SYSTEM COST model).

These multiple regression models were considered to be "optimal" given the available data. These models maximally use the information contained in the three available predictors to explain production cost.

E. OPTIMUM REGRESSION MODEL DISPLAYS

The following four regression models are provided with relevant statistics and visual plots of the regression residuals vs $\hat{Y}_c^2$. These data are displayed to support this study's results and conclusions concerning the selection of the optimum regression models in Figures 4-7.

F. CONCLUSIONS

Note that model 2 explains a greater proportion of PLATFORM COST than does model 1 for AIRFRAME COST. Since the two models contain the same predictor variables, this result is consistent with PLATFORM STAND and PLATFORM ADVANCE being surrogates for frame technology, and measuring technology state of the art and extensions for airframes with "noise."

Also note that the regression for SYSTEM COST yields the poorest result. This is expected given that SYSTEM COST < SYSTEM STAND and SYSTEM ADVANCE are all derived measures, constructed from other available COST and technology measures.

The analysis of hypothesis one indicates that the overall technology embodied in an aircraft, as measured by REACH, is highly associated with production cost. The analysis, however, indicates that REACH is a redundant variable when ADVANCE and STAND are available.

² $\hat{Y}_c$ is defined as the predicted value of the regression equation.

AIRFRAME COST = +f(STAND, ADVANCE, SERIES)

LOG(CACF) = -0.127 + .0857(STAND) + .0866(ADVANCE) -
0.206(SERIES)

STANDARD DEVIATION = 0.2045

	T-RATIO	P-TEST
CONSTANT	-0.90	0.375
STAND	6.18	0.000
ADVANCE	4.97	0.000
SERIES	-2.82	0.008

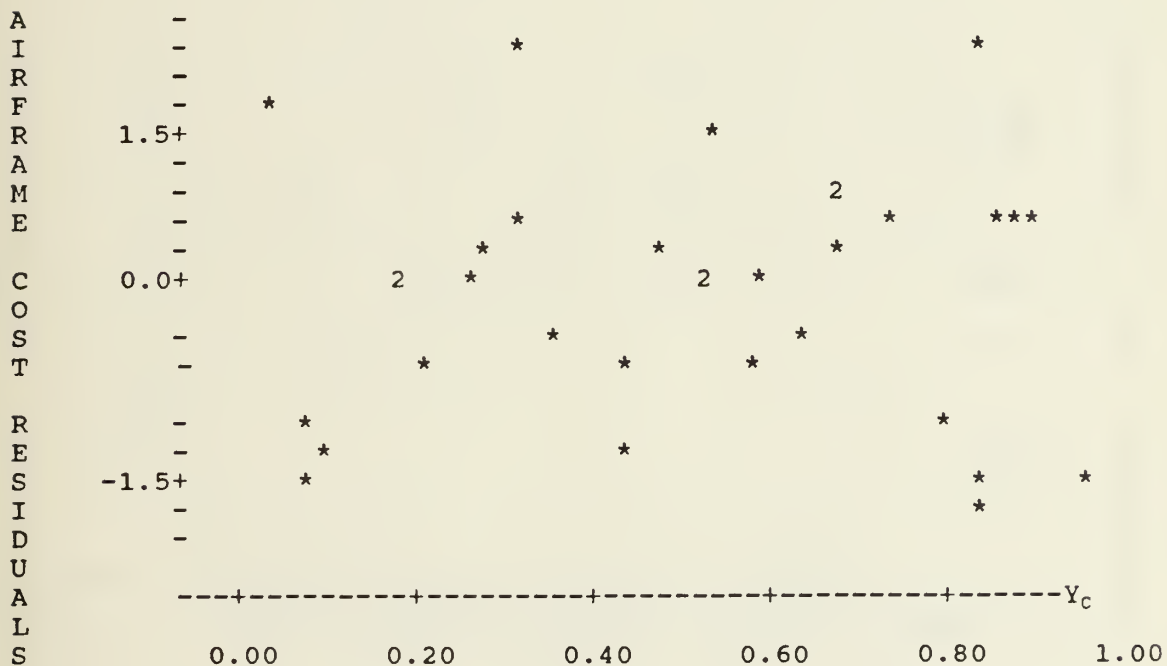
R-SQUARED (ADJUSTED) = 67.6%

F-TEST = 24.62

DURBIN-WATSON STATISTIC = 1.89

CORRELATION:

	LOGCACF	STAND	ADVANCE
STAND	0.516		
ADVANCE	0.458	0.000	
SERIES	-0.477	-0.045	-0.212



N* = 12

Figure 4. Airframe Cost Residuals vs Yc

PLATFORM COST = +f(STAND, ADVANCE, SERIES)

LOG(CACE) = -0.08 + .0914(STAND) + .0805(ADVANCE) -
0.214(SERIES)

STANDARD DEVIATION = 0.1807

	T-RATIO	P-TEST
CONSTANT	-0.64	0.525
STAND	7.47	0.000
ADVANCE	5.24	0.000
SERIES	-3.31	0.002

R-SQUARED (ADJUSTED) = 73.6%

F-TEST = 32.62

DURBIN-WATSON STATISTIC = 1.69

CORRELATION:

	LOGCACE	STAND	ADVANCE
STAND	0.580		
ADVANCE	0.458	0.000	
SERIES	-0.477	-0.045	-0.212

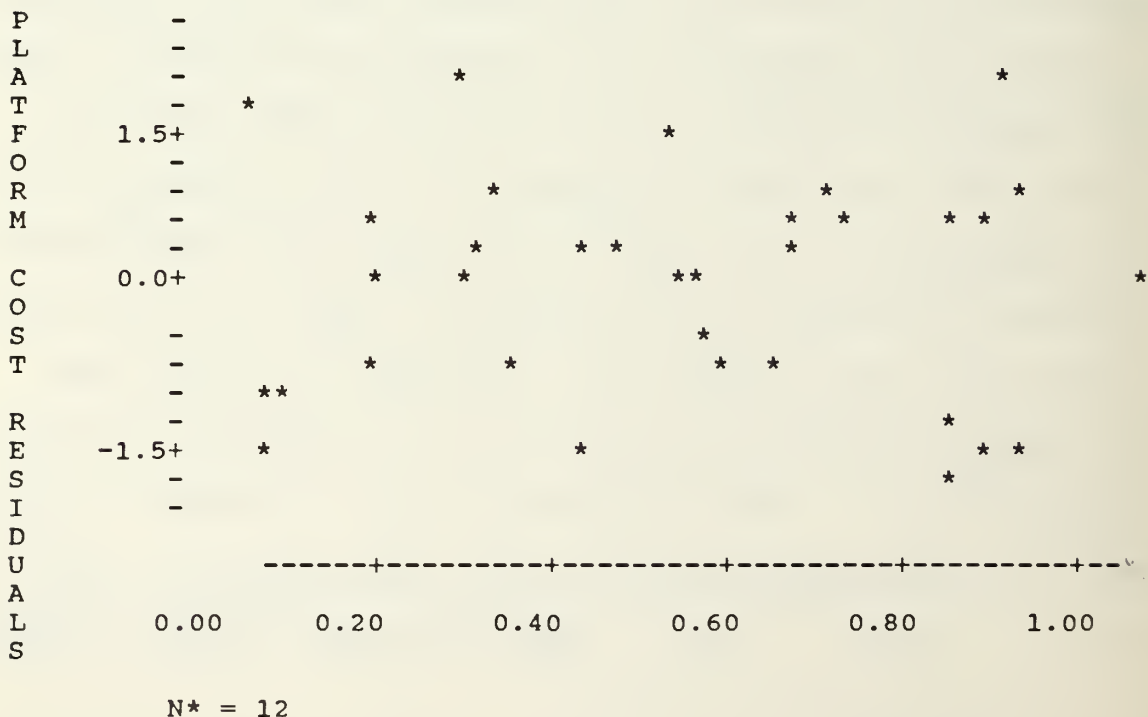


Figure 5. Platform Cost Residuals vs Y_c .

SYSTEM COST = +f(STAND, ADVANCE, SERIES)

LOG(CACS) = -1.53 + 1.22(STAND) + .574(ADVANCE) -
0.2(SERIES)

STANDARD DEVIATION = 0.4176

	T-RATIO	P-TEST
CONSTANT	-5.35	0.000
STAND	5.33	0.000
ADVANCE	2.22	0.034
SERIES	-1.37	0.182

R-SQUARED (ADJUSTED) = 49.8%

F-TEST = 11.58

DURBIN-WATSON STATISTIC = 1.89

CORRELATION:

	LOGCACS	STAND	ADVANCE
STAND	0.656		
ADVANCE	0.242	0.000	
SERIES	-0.216	-0.045	-0.111

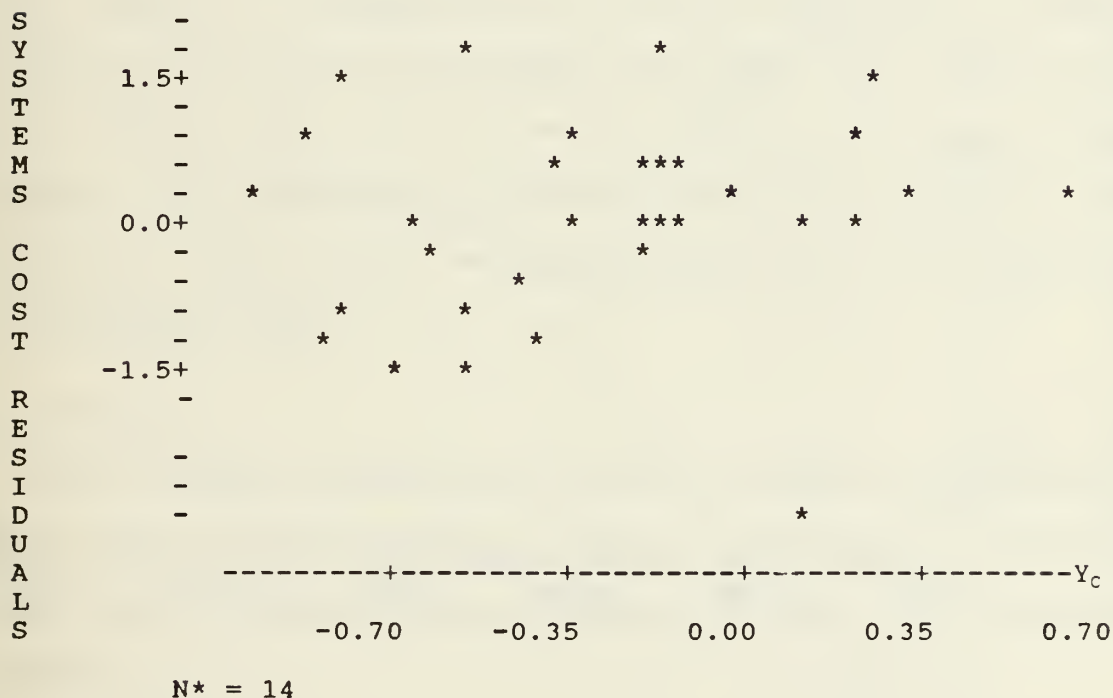


Figure 6. Systems Cost Residuals vs Y_c

FLYAWAY COST = +f(STAND, ADVANCE, SERIES)

LOG(CACA) = 0.375 + .0419(STAND) + .0393(ADVANCE) -
0.241(SERIES)

STANDARD DEVIATION = 0.1847

	T-RATIO	P-TEST
CONSTANT	5.07	0.000
STAND	8.35	0.000
ADVANCE	6.31	0.000
SERIES	-4.00	0.000

R-SQUARED (ADJUSTED) = 76.8%

F-TEST = 41.91

DURBIN-WATSON STATISTIC = 1.77

CORRELATION:

	LOG(CACA)	STAND	ADVANCE
STAND	0.631		
ADVANCE	0.480	0.000	
SERIES	-0.395	-0.045	-0.100

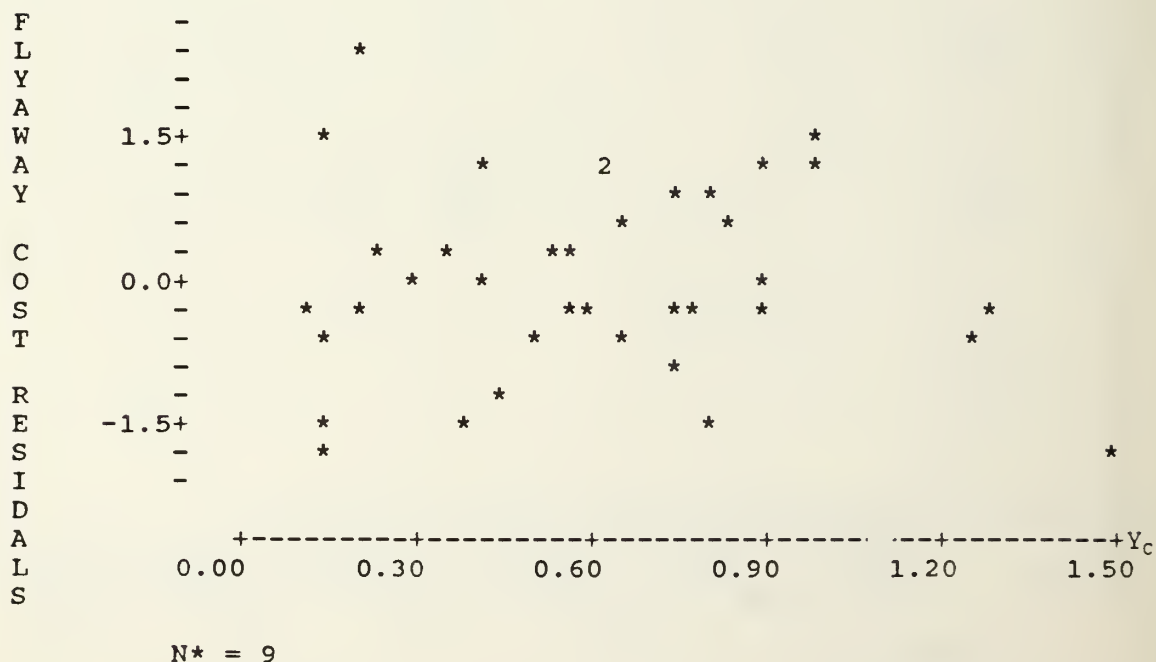


Figure 7. Flyaway Cost Residuals vs Y_c

The analysis of hypothesis two indicates that production costs do indeed increase with the increase in the state of the art in technology. The findings for STAND (R-type) clearly support this conclusion.

Analysis of hypothesis three leads to the conclusion that ADVANCE (R-type) is also a significant predictor of production cost. Cost increases as a function of the degree of technological extension of a program.

Hypothesis four was clearly demonstrated throughout testing by the improvement of R-squared once the SERIES variable was added. The only model where this observation is weak is in the SYSTEMS COST model. The t-ratio and p-test indicate that SERIES is insignificant, but the addition of SERIES improved the R-squared (adjusted) value by 1.5%. This follows the findings noted for the other models, only to a lesser degree. Follow-on series of existing designs do produce lower production costs and new design programs result in a "premium" in production cost.

G. SUMMARY

This chapter has described the three central hypotheses of this study and the procedures used to test the relationships which exist between aircraft production costs and technology variables.

Multiple regression testing, being the test method of choice, provided significant findings during the analysis.

The results of each step of testing highlighted the need for and direction of further work.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The methods and procedures employed within this study effectively demonstrate that relevant models can be developed for describing the relationships which exist between measures of the technology in complex aircraft systems and production cost.

B. DATA

The building of accurate and valid technology measures is critical to effective research in this field. Without accurate data, problems of "noise" or erroneous models will result.

Accurate cost records must be retained within DOD. A uniform system of accounting standards has only recently been employed within DOD. This has only partially solved the problem of accurate records. The cost records are, for the most part, not computerized for ease of access and are not easily applied to analysis. Without accurate data uniformly collected by all branches of DOD future attempts to develop models explaining cost will be difficult.

This study encountered a problem in attempting to model SYSTEMS COST. This can, in part, be attributed to the lack of accurate cost data for SYSTEMS COST and the need for the study

to reconstruct SYSTEMS COST and SYSTEMS STAND and ADVANCE measures from other available data. Additionally, no measure of AIRFRAME technology was available, so a surrogate measure was used in the analysis of AIRFRAME COST.

C. METHODOLOGICAL REFINEMENTS

When working with regression analysis techniques, it is recommended that a refined application of variable analysis be applied prior to working with the data. The dependent and independent variables must be evaluated for linearity, constant variance, normal distribution and independence of residuals. Within this study, those determinations were critical to generating the most accurate models. Several adjustments were made to the data, based on the problems found by using these techniques.

Transformation techniques were central to resolving these initial problems. Transformation of the cost variables by calculating the natural log for costs, "cleaned up" the data base, ensuring valid test results. It is recommended that all future test involving relationships between cost and performance variables within complex system be initially evaluated and adjusted where necessary using similar transformation techniques.

D. CHOICE OF PREDICTOR VARIABLES

Initial regression analysis models demonstrated that inclusion of REACH, STAND and ADVANCE within the same regression

model produced incompatible results. This was the primary reason for ultimately dropping REACH from the analysis. (REACH was redundant.) Additionally, several weak variables were dropped from the analysis [STAND (P) and ADVANCE (P)]. Each application of these weak variables produced sharp reductions in significance of the models. Based on these observations the insignificant variables were removed from testing.

E. HYPOTHESIS TESTING AND MODEL CONSTRUCTION

After the optimum independent variables were established, concentrated testing of those variables produced the models discussed in Chapter VI. All models were highly significant, linear, normally distributed, possessed constant variance and independence.

Analysis of the data with regard to the central hypotheses, established that specific relationships do exist between aircraft system cost and the technology measures developed for this study. STAND and ADVANCE, in combination with the SERIES "dummy" variable were the measures that most successfully explained production cost.

The accuracy of these results rests on the accuracy of the TASC study and the methodologies TASC used to develop the initial measures of production cost and aircraft performance.

F. RECOMMENDATIONS

Recommendations for further study and potential thesis research topics include the following:

1. Test for relationships within other mission and flight profile areas (e.g., bombers, helicopters, or patrol aircraft).

The researcher will need to adjust the data base to a new "baseline" aircraft. This realignment will validate the performance figures of merit tables. Considerations would include selecting aircraft of similar design and performance characteristics (e.g., VTOL or STOL).

The value of such a study would be the extension of work on technology/cost relationships into another data base to determine if relationships similar to the ones found in this study can be generalized.

2. Additional research is recommended for refining this study every ten years or whenever significant advances in future aircraft technology and production developments are achieved.

This project would include a comparative review of this study comparing the future trends of aircraft cost vs performance.

3. A detailed review of the TASC methodology for developing cost measures and performance measures is advised. This study would have two primary objectives:

- a. Develop an accurate SYSTEM COST measure.
- b. Develop an accurate AIRFRAME TECHNOLOGY measure.

The benefit of such a study would be the elimination of the "noise" or inaccuracy which exist within this study. The ultimate goal would be an optimal set of aircraft cost/performance relationship models which were not the direct result of ad hoc research techniques.

G. SUMMARY

This thesis could be used as the foundation for future research on the relationships between aircraft system costs and their associated advances in technology.

The results of this study answer many academic questions concerning these relationships. The use of this study's regression models for DOD program management is not recommended until the "noise" is eliminated from the data base.

APPENDIX

The Appendix contains the data base obtained from the TASC Research Methodology (Program COST, REACH, and STARTYR). The log cost, technology measures (STAND, ADVANCE) and SERIES (dummy variable) are developed measures used throughout this study.

PROGRAM COST DATA

ROW	AIRFRAME	PLATFORM	FLYAWAY	SYSTEM	PROGRAM
1	*	*	*	*	A-1J
2	1.212	1.557	1.703	0.146	A-1E/G/H
3	5.136	6.007	7.815	1.808	A-3A/B
4	1.669	1.893	2.100	0.207	A-4C
5	2.225	2.927	3.714	0.787	A-4M
6	1.603	1.852	1.917	0.065	A-4A/B
7	1.875	2.436	2.675	0.239	A-4E/F
8	11.286	12.421	13.123	0.702	A-6A
9	7.656	8.883	10.846	1.963	A-6E
10	2.950	3.847	5.012	1.165	A-7D
11	3.901	4.855	5.000	0.145	A-7E
12	3.217	4.511	5.272	0.761	A-7A/B
13	4.196	5.748	7.272	1.524	A-10A
14	2.229	2.297	2.388	0.091	F-1B/C/M
15	*	*	*	*	A/AF-1E
16	*	*	*	*	F-2C
17	3.419	4.205	4.710	0.505	F-3A/B/C
18	3.649	4.479	5.919	1.440	F-4E
19	3.511	4.416	5.924	1.508	F-4J
20	7.202	8.802	9.613	0.811	F-4A/B
21	*	*	5.753	*	F-4C/D
22	*	*	*	*	F-6A
23	3.746	4.334	4.475	0.141	F-8A/B/C
24	*	*	*	*	F-9J
25	0.655	0.856	0.939	0.083	F-9F/H
26	*	*	*	*	F-11A
27	13.082	17.333	23.901	6.568	F-14A
28	10.252	15.446	19.356	3.910	F-15A
29	4.045	6.069	9.641	3.572	F-16A
30	18.654	22.197	23.968	1.771	F/A-18A
31	6.520	6.020	5.943	-0.077	F-84F
32	0.752	1.118	1.458	0.340	F-86D
33	0.887	1.028	1.095	0.067	F-86F
34	*	*	*	*	F-86H
35	*	*	*	*	F-89C
36	2.471	2.831	3.496	0.665	F-89D
37	1.698	2.426	2.659	0.233	F-100D
38	2.939	3.709	3.856	0.147	F-100A/C
39	5.771	6.735	7.291	0.556	F-101A/B
40	6.802	8.125	9.206	1.081	F-102A
41	2.004	3.830	3.773	-0.057	F-104A/B
42	10.047	10.952	12.280	1.328	F-105B/D
43	7.014	7.897	12.016	4.119	F-106A/B
44	*	*	23.510	*	F-111A
45	*	*	*	*	F-111B
46	*	*	24.141	*	F-111D
47	9.827	14.121	20.897	6.776	F-111F

* INDICATES DATA NOT AVAILABLE

ALL PROGRAM COST DATA IN ACTUAL \$MILLIONS

NATURAL LOG (COSTS)

ROW	AIRFRAME	PLATFORM	FLYAWAY	SYSTEMS	PROGRAM
1	*	*	*	*	A-1J
2	0.08350	0.19229	0.23121	-0.83565	A-1E/G/H
3	0.71063	0.77866	0.89293	0.25720	A-3A/B
4	0.22246	0.27715	0.32222	-0.68403	A-4C
5	0.34733	0.46642	0.56984	-0.10403	A-4M
6	0.20493	0.26764	0.28262	-1.18709	A-4A/B
7	0.27300	0.38668	0.42732	-0.62160	A-4E/F
8	1.05254	1.09416	1.11803	-0.15366	A-6A
9	0.88400	0.94856	1.03527	0.29292	A-6E
10	0.46982	0.58512	0.70001	0.21748	A-7D
11	0.59118	0.68619	0.69897	-0.83863	A-7E
12	0.50745	0.65427	0.72198	-0.11862	A-7A/B
13	0.62284	0.75952	0.86165	0.18298	A-10A
14	0.34811	0.36116	0.37803	-1.04096	F-1B/C/M
15	*	*	*	*	F/AF-1E
16	*	*	*	*	F-2C
17	0.53390	0.62377	0.67302	-0.29671	F-3A/B/C
18	0.56217	0.65118	0.77225	0.15836	F-4E
19	0.54543	0.64503	0.77262	0.17840	F-4J
20	0.85745	0.94458	0.98286	-0.09098	F-4A/B
21	*	*	0.75989	*	F-4C/D
22	*	*	*	*	F-6A
23	0.57357	0.63689	0.65079	-0.85078	F-8A/B/C
24	*	*	*	*	F-9J
25	-0.18376	-0.06753	-0.02733	-1.08092	F-9F/H
26	*	*	*	*	F-11A
27	1.11667	1.23887	1.37842	0.81743	F-14A
28	1.01081	1.18882	1.28682	0.59218	F-15A
29	0.60692	0.78312	0.98412	0.55291	F-16A
30	1.27077	1.34629	1.37963	0.24822	F/A-18A
31	0.81425	0.77960	0.77401	*	F-84F
32	-0.12378	0.04844	0.16376	-0.46852	F-86D
33	-0.05208	0.01199	0.03941	-1.17393	F-86F
34	*	*	*	*	F-86H
35	*	*	*	*	F-89C
36	0.39287	0.45194	0.54357	-0.17718	F-89D
37	0.22994	0.38489	0.42472	-0.63264	F-100D
38	0.46820	0.56926	0.58614	-0.83268	F-100A/C
39	0.76125	0.82834	0.86279	-0.25493	F-101A/B
40	0.83264	0.90982	0.96407	0.03383	F-102A
41	0.30190	0.58320	0.57669	*	F-104A/B
42	1.00204	1.03949	1.08920	0.12320	F-105A/B
43	0.84597	0.89746	1.07976	0.61479	F-106A/B
44	*	*	1.37125	*	F-111A
45	*	*	*	*	F-111B
46	*	*	1.38276	*	F-111D
47	0.99242	1.14987	1.32008	0.83097	F-111F

* INDICATES DATA NOT AVAILABLE

REACH

ROW	PLATFORM	FLYAWAY	SYSTEM	PROGRAM
1	6.57	3.34	0.50837	A-1J
2	6.57	3.34	0.50837	A-1E/G/H
3	12.84	10.74	0.83645	A-3A/B
4	6.22	5.45	0.87621	A-4C
5	7.33	8.52	1.16235	A-4M
6	6.84	3.93	0.57456	A-4A/B
7	7.22	7.27	1.00693	A-4E/F
8	12.13	13.83	1.14015	A-6A
9	12.13	22.40	1.84666	A-6E
10	10.73	16.17	1.50699	A-7D
11	11.59	19.77	1.70578	A-7E
12	11.57	12.10	1.04581	A-7A/B
13	11.03	12.12	1.09882	A-10A
14	5.90	5.29	0.89661	F-1B/C/M
15	6.05	5.44	0.89917	F/AF-1E
16	6.13	3.91	0.63785	F-2C
17	7.30	9.02	1.23562	F-3A/B/C
18	10.17	13.96	1.37266	F-4E
19	10.31	13.39	1.29874	F-4J
20	10.31	9.32	0.90398	F-4A/B
21	10.00	10.07	1.00700	F-4C/D
22	7.60	7.58	0.99737	F-6A
23	8.40	8.40	1.00000	F-8A/B/C
24	4.72	4.02	0.85169	F-9J
25	5.00	4.19	0.83800	F-9F/H
26	6.35	5.80	0.91339	F-11A
27	14.44	31.51	2.18213	F-14A
28	12.11	16.14	1.33278	F-15A
29	11.56	15.69	1.35727	F-16A
30	11.60	25.42	2.19138	F/A-18
31	7.85	5.13	0.65350	F-84F
32	5.31	3.68	0.69303	F-86D
33	5.09	4.03	0.79175	F-86F
34	6.08	5.68	0.93421	F-86H
35	3.72	2.46	0.66129	F-89C
36	4.72	4.05	0.85805	F-89D
37	6.25	5.99	0.95840	F-100D
38	5.51	4.80	0.87114	F-100A/C
39	9.69	13.35	1.37771	F-101A/B
40	8.02	9.71	1.21072	F-102A
41	6.64	6.79	1.02259	F-104A/B
42	11.68	14.86	1.27226	F-105B/D
43	9.58	13.05	1.36221	F-106A/B
44	15.45	18.46	1.19482	F-111A
45	16.48	24.81	1.50546	F-111B
46	16.48	24.39	1.47998	F-111D
47	16.48	31.01	1.88167	F-111F

STAND (R)

ROW	PLATFORM	FLYAWAY	SYSTEM	PROGRAM
1	7.7244	7.9013	0.9536	A-1J
2	6.8329	5.7825	0.8450	A-1E/G/H
3	7.1301	6.4888	0.8812	A-3A/B
4	8.3188	9.3138	1.0260	A-4C
5	12.1819	18.4952	1.4967	A-4M
6	7.1301	6.4888	0.8812	A-4A/B
7	9.5074	12.1388	1.1709	A-4E/F
8	9.5074	12.1388	1.1709	A-6A
9	12.1819	18.4952	1.4967	A-6E
10	11.5875	17.0826	1.4243	A-7D
11	11.5875	17.0826	1.4243	A-7E
12	10.6961	14.9639	1.3157	A-7A/B
13	13.6677	22.0265	1.6777	A-10A
14	6.8329	5.7825	0.8450	F-1B/C/M
15	7.4273	7.1950	0.9174	F/AF-1E
16	6.5358	5.0763	0.8088	F-2C
17	6.8329	5.7825	0.8450	F-3A/B/C
18	10.9932	15.6701	1.3519	F-4E
19	10.9932	15.6701	1.3519	F-4J
20	8.9131	10.7263	1.0984	F-4A/B
21	9.8046	12.8451	1.2071	F-4C/D
22	7.1301	6.4888	0.8812	F-6A
23	7.7244	7.9013	0.9536	F-8A/B/C
24	7.7244	7.9013	0.9536	F-9J
25	6.5358	5.0763	0.8088	F-9F/H
26	7.1301	6.4888	0.8812	F-11A
27	12.4790	19.2014	1.5329	F-14A
28	13.0734	20.6139	1.6053	F-15A
29	14.5592	24.1452	1.7863	F-16A
30	14.8563	24.8515	1.8225	F/A-18A
31	6.5358	5.0763	0.8088	F-84F
32	6.5358	5.0763	0.8088	F-86D
33	6.5358	5.0763	0.8088	F-86F
34	6.8329	5.7825	0.8450	F-86H
35	6.2386	4.3700	0.7726	F-89C
36	6.5358	5.0763	0.8088	F-89D
37	7.4273	7.1950	0.9174	F-100D
38	6.8329	5.7825	0.8450	F-100A/C
39	7.4273	7.1950	0.9174	F-101A/B
40	7.1301	6.4888	0.8812	F-102A
41	8.0216	8.6075	0.9898	F-104A/B
42	8.3188	9.3138	1.0260	F-105B/D
43	8.3188	9.3138	1.0260	F-106A/B
44	10.6961	14.9639	1.3157	F-111A
45	10.9932	15.6701	1.3519	F-111B
46	11.5875	17.0826	1.4243	F-111D
47	12.1819	18.4952	1.4967	F-111F

ADVANCE (R)

ROW	PLATFORM	FLYAWAY	SYSTEM	PROGRAM
1	-1.15440	-4.5613	-0.445230	A-1J
2	-0.26290	-2.4425	-0.336630	A-1E/G/H
3	5.70990	4.2512	-0.044750	A-3A/B
4	-2.09880	-3.8638	-0.149790	A-4C
5	-4.85190	-9.9752	-0.334350	A-4M
6	-0.29010	-2.5588	-0.306640	A-4A/B
7	-2.28740	-4.8688	-0.163970	A-4E/F
8	2.62260	1.6912	-0.030750	A-6A
9	-0.05190	3.9048	0.349960	A-6E
10	-0.85750	-0.9126	0.082690	A-7D
11	0.00250	2.6874	0.281480	A-7E
12	0.87390	-2.8639	-0.269890	A-7A/B
13	-2.63770	-9.9065	-0.578880	A-10A
14	-0.93290	-0.4925	0.051610	F-1B/C/M
15	-1.37730	-1.7550	-0.018230	F/AF-1E
16	-0.40580	-1.1663	-0.170950	F-2C
17	0.46710	3.2375	0.390620	F-3A/B/C
18	-0.82320	-1.7101	0.020760	F-4E
19	-0.68320	-2.2801	-0.053160	F-4J
20	1.39690	-1.4063	-0.194420	F-4A/B
21	0.19540	-2.7751	-0.200100	F-4C/D
22	0.46990	1.0912	0.116170	F-6A
23	0.67560	0.4987	0.046400	F-8A/B/C
24	-3.00440	-3.8813	-0.101910	F-9J
25	-1.53580	-0.8863	0.029200	F-9F/H
26	-0.78010	-0.6888	0.032190	F-11A
27	1.96100	12.3086	0.649230	F-14A
28	-0.96340	-4.4739	-0.272520	F-15A
29	-2.99920	-8.4552	-0.429030	F-16A
30	-3.25630	0.5685	0.368880	F/A-18A
31	1.31420	0.0537	-0.155300	F-84F
32	-1.22580	-1.3963	-0.115770	F-86D
33	-1.44580	-1.0463	-0.017050	F-86F
34	-0.75290	-0.1025	0.089210	F-86H
35	-2.51860	-1.9100	-0.111310	F-89C
36	-1.81580	-1.0263	0.049250	F-89D
37	-1.17730	-1.2050	0.041000	F-100D
38	-1.32290	-0.9825	0.026140	F-100A/C
39	2.26270	6.1550	0.460310	F-101A/B
40	0.88990	3.2212	0.329520	F-102A
41	-1.38160	-1.8175	0.032790	F-104A/B
42	3.36120	5.5462	0.246260	F-105B/D
43	1.26120	3.7362	0.336210	F-106A/B
44	4.75390	3.4961	-0.120880	F-111A
45	5.48680	9.1399	0.153560	F-111B
46	4.89250	7.3074	0.055680	F-111D
47	4.29810	12.5148	0.384970	F-111F

PRODUCTION CYCLE DATA

ROW	START YEAR	END YEAR	SERIES	PROGRAM
1	55	55	1	A-1J
2	52	54	1	A-1E/G/H
3	53	59	0	A-3A/B
4	57	62	1	A-4C
5	70	77	1	A-4M
6	53	57	0	A-4A/B
7	61	67	1	A-4E/F
8	61	69	0	A-6A
9	70	79	1	A-6E
10	68	75	1	A-7D
11	68	79	1	A-7E
12	65	67	0	A-7A/B
13	75	82	0	A-10A
14	52	55	0	F-1B
15	54	55	1	F/AF-1E
16	51	51	0	F-2C
17	52	58	0	F-3A/B/C
18	66	74	1	F-4E
19	66	70	1	F-4J
20	59	66	0	F-4A/B
21	62	66	1	F-4C/D
22	53	54	0	F-6A
23	55	58	0	F-8A/B/C
24	55	56	1	F-9J
25	51	52	1	F-9F/H
26	53	55	0	F-11A
27	71	82	0	F-14A
28	73	79	0	F-15A
29	78	82	0	F-16A
30	79	82	0	F/A-18
31	51	53	1	F-84F
32	51	53	1	F-86D
33	51	53	1	F-86F
34	52	53	1	F-86H
35	50	51	1	F-89C
36	51	54	1	F-89D
37	54	56	1	F-100D
38	52	55	0	F-100A/C
39	54	59	0	F-101A/B
40	53	57	0	F-102A
41	56	57	0	F-104A/B
42	57	62	0	F-105B/D
43	57	59	0	F-106A/B
44	65	67	0	F-111A
45	66	66	1	F-111B
46	68	70	1	F-111D
47	70	74	1	F-111F

FON: (0)= INITIAL PROGRAM, (1)= FOLLOW-ON PROGRAM

LIST OF REFERENCES

1. Timperlake, E.T., The TASCFORM-AIR Model, A Technique for Assessing Comparative Force Modernization in Tactical Aviation, Volume 1: Methodology Development, TR-1334-3, The Analytic Sciences Corporation (TASC), Arlington, Virginia, February 1980.
2. Greer, W.E., Jr., A Method for Estimating and Controlling the Cost of Extending Technology, Naval Postgraduate School, Monterey, California, March 1988.
3. Dodson, E.N., and Graver, C.A., An Approach to Quantitative Measurement of Advances in State of the Art, Internal Memorandum (Releasable) IMR-997, General Research Corporation, Santa Barbara, California, June 1969.
4. DePuy, W.E., Jr., US Tactical Aircraft Cost Handbook, Volume 1: Preliminary Analysis, TR-807-2R, The Analytical Sciences Corporation (TADC), Arlington, Virginia, June 1981.
5. DePuy, W.E., Jr., US Military Aircraft Cost Handbook, TR-8203-1, The Analytic Sciences Corporation (TASC), Arlington, Virginia, March 1983.

BIBLIOGRAPHY

- Anderson, T.W., and Sclove, S.L., Minitab Guide to the Statistical Analysis of Data, The Scientific Press, 1987.
- Bridgman, Leonard, Jane;s All The Worlds Aircraft, Sampson, Low, Marston & Co., Years 1947-1980.
- DePuy, W.E., Jr., Task IA Report: Feasibility Study for Integrating a Cost Methodology into the TASCFORM-AIR Model, TR-8007-1R, The Analytic Sciences Corporation (TASC), Arlington, Virginia, 18 November 1980.
- Levine, D.M., Berenson, M.L., and Stephan, D., Using Minitab with Basic Business Statistics, Prentice-Hall, Inc., 1986.
- Liao, S.S., Unpublished Manuscript, Naval Postgraduate School, Monterey, California.
- Mingos, Howard, The Aircraft Year Book, Lanciar Publishers, Inc., Years 1947, 1950, 1951, 1952, 1953, 1954.
- Taylor, J.W.R., Combat Aircraft of the World, 1909 to the Present, G.P. Putnam & Sons, New York, New York, 1969.
- Weiss, N.A., and Hassett, M.J., Introductory Statistics, and Minitab Supplement, Addison-Wesley Publishing Company, 1987.

INITIAL DISTRIBUTION LIST

	No. Copies
1. Defense Technical Information Center Cameron Station Alexandria, Virginia 22304-6145	2
2. Library, Code 0142 Naval Postgraduate School Monterey, California 93943-5002	2
3. Professor D. Moses, Code 54Mo Naval Postgraduate School Monterey, California 93943-5000	1
4. LCDR D. Matthews, Code 54Ma Naval Postgraduate School Monterey, California 93943-5000	1
5. LCDR R.E. Lowe, USNR Naval Reserve Force 4400 Daluphine St. Code 6111 New Orleans, LA 70146	1

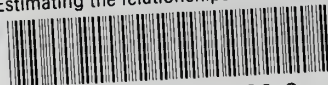
Thesis

L85744 Lowe

c.1 Estimating the relationships between the state of the art of technology and production cost for U.S. aircraft.

thesL85744

Estimating the relationships between the



3 2768 000 82882 6

DUDLEY KNOX LIBRARY